MATLAB™ MODELLING OF THE HIGH POWER SADM

Analysis and Testing of Back Electro-Motive Force Behaviour and Torque Margin when Driving Large Solar Arrays

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ABSTRACT

Solar Array Drive Mechanisms (SADMs) perform a crucial role as they rotate Spacecraft Solar Arrays (SA's) when in orbit to ensure that the SA is always pointing at the Sun for maximum power generation. Failure of a SADM could cripple the spacecraft. Because of this important role, it is important to try to recreate the actual environment experienced by the SADM in orbit during the qualification campaign, i.e. "Test how we fly and fly how we test". It is impossible to recreate exactly the in-orbit behaviour of the SA on the ground because deployed SA's are becoming increasing longer and larger and gravity can have a significant influence on the on-ground performance and responses.

This paper discusses the techniques used during the High Power SADM (HP-SADM) design and qualification campaign to ensure that the new generation SADM is capable of driving the largest SA's envisaged for the next generation telecommunication satellites.

1. INTRODUCTION

The next generation Solar Array Drive Mechanism (SADM) now in development at EADS Astrium Stevenage is the High Power SADM. This SADM is designed to cope with the highest power solar arrays currently being envisaged for the next generation telecommunications satellites. Higher power solar arrays imply larger and heavier solar arrays. This means that the SADM needs to produce more torque to rotate the array, so the in-orbit array behaviour becomes more critical, and hence the need to test the SADM under the conditions and responses caused by the solar arrays in orbit becomes more important.

As it is impossible to recreate the in-orbit behaviour of the solar array on the ground, it was decided to use MATLAB™ and SIMULINK™ to create a mathematical model of the SADM coupled to the solar array. The development team would then validate the mathematical model by correlating with real-life test data. This would allow the team to modify various parameters to simulate the in-orbit behaviour of the array, and predict the likely impact on the SADM during its in-orbit life.

This development aimed to address four important aspects:

1. Asses the SADM stepping drive behaviour to validate that it will not excite the array and results in stable array oscillations.
2. Validate that normal array oscillations will not cause the SADM to miss-step.
3. Assessment of the torque seen by the SADM caused by the oscillating array?
4. Assessment of the oscillating array behaviour in respect of a change to the Back Electromotive Force behaviour (BEMF) of the SADM stepper motor.

2. THE HIGH POWER SOLAR ARRAY DRIVE MECHANISM

The High Power Solar Array Drive Mechanism consists of a bi-phase, bi-polar 45° stepper motor, planetary gearbox, a spur gearbox, a main bearing pair, a potentiometer, and a power and signal slip ring. These components are integrated on a common base-plate.

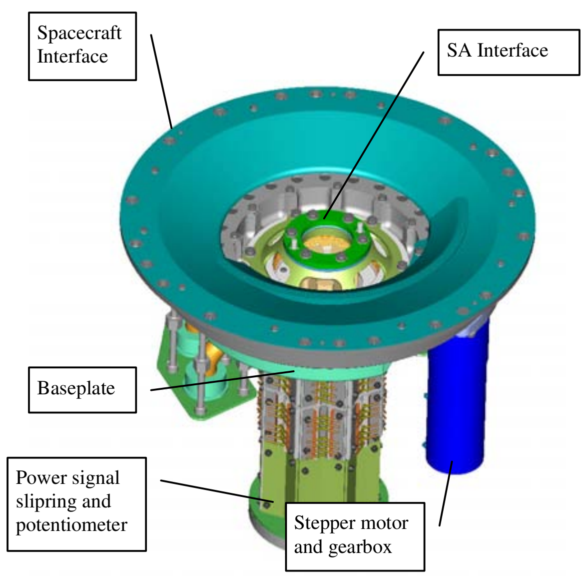

Figure 1, High Power Solar Array Drive mechanism

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3. THE BI-POLAR 45° STEPPER MOTOR

The Stepper motor consists of prime and redundant coils mounted on a common shaft. Torque is generated by energising the coils in sequence. This sequencing leads to the motor shaft rotating in a stepping sequence. Each energisation sequence leads to a 45° movement of the motor shaft.

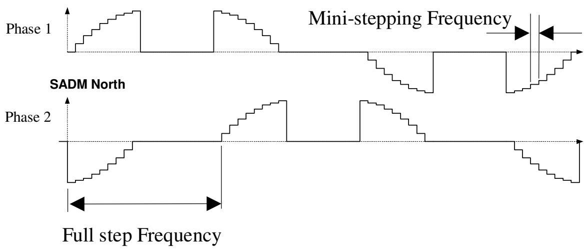

Figure 2. Mini-stepping Stepper Motor Drive Profile

Astrium utilise a mini-stepping current controlled drive profile as shown in Fig 2 to control the speed of the stepper motor. This mini-stepping profile means that there are two fundamental frequencies in the motor torque profile, the mini-stepping frequency and the full step frequency. Both of these frequencies have the potential to excite the SA's. The SADM drive electronics change the mini-stepping and the full step frequencies in order to change the speed of the SADM. The SADM runs at 1 or 20 Revolutions per Day (RPD); therefore two mini-stepping frequencies and two full step frequencies are apparent in the operational envelope of the SADM.

In order to model the stepper motor in MATLAB™ / Simulink™, a thorough understanding of stepper motor physics is required.

A stepper motor can be described mathematically by:

Motor torque:

$$T_{MOTOR} = K\left[-I_1 \sin(p\theta) + I_2 \cos(p\theta)\right] \quad (1)$$

Detent torque:

$$T_{DETENT} = T_{MAXDETENT}\left[\sin(2np\theta) + \sin(2np\theta + \varphi)\right] \quad (2)$$

Motor mechanical equation:

$$T_{MOTOR} - T_{DETENT} = J\frac{d^2\theta}{dt^2} + T_{VIS}\frac{d\theta}{dt} \quad (3)$$

Coil voltages :

$$V_1 = RI_1 + L\frac{dI_1}{dt} - K\frac{d\theta}{dt}\sin(p\theta) \quad (4)$$

$$V_2 = RI_2 + L\frac{dI_2}{dt} - K\frac{d\theta}{dt}\sin(p\theta) \quad (5)$$

Viscous friction due to damping coils:

$$T_{VIS} = \left[\frac{K\left(\frac{\text{No of damp coils}}{\text{No of motor coils}}\right)^2}{R_{DPG}}\right] \quad (6)$$

Where:

Variable	Description	Units
K	Stepper motor electrical constant	Nm/A
T_{DETENT}	Detent torque	Nm
$T_{MAXDETENT}$	Maximum detent torque	Nm
T_{VIS}	Viscous torque constant	Nm/(rad/s)
T_F	Friction torque	Nm
I_1	Current in the motor coil 1	A
I_2	Current in the motor coil 2	A
p	Number of motor poles pairs.	
n	Number of motor phases	
θ	Motor shaft position	rad
φ	Stack angle	rad
R_{DPG}	Damping Coils resistance	Ω

As can be seen by the Equations 1 and 2, both the amplitude of the torque generated by the coils and the inherent detent torque depend on the shaft position. The motor shaft position depends on the inertia of the gearbox it is attached to, and ultimately, the inertia of the SA.

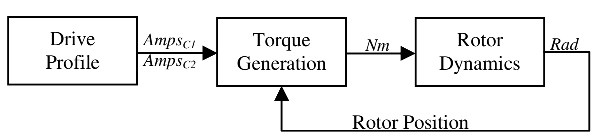

Figure 3. MATLAB™ Modelling Flow Diagram

Fig. 3 shows a flow diagram depicting how the stepper motor was modelled in MATLAB™. The rotor position feeding back into the torque generation block.

4. THE SADM DYNAMICS

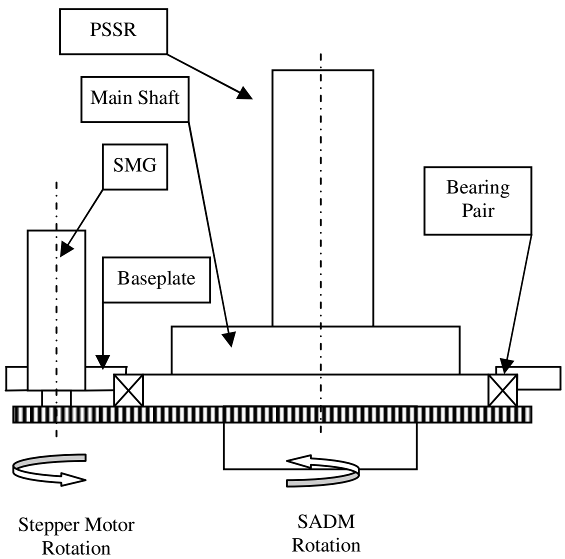

Figure 4, SADM Layout

Fig 4 shows the general layout of the HP-SADM. The SMG (Stepper Motor and planetary Gearbox) is coupled to the HP-SADM output shaft by a spur gearbox.

4.1, The SMG

The SMG is treated as a single mechanical dynamic system where the sum of the inertias includes the motor rotor inertia and the planetary gearbox inertia.

$$\Sigma_{INERTIA} = J = J_{ROTOR} + J_{PLANET\ GEARBOX} \qquad (7)$$

The SMG viscous friction parameter is very difficult to predict, so a value was derived by studying the logarithmic decrement of an SMG BEMF (Back Electromotive Force) plot. Because of this parameters derivation, it effectively covers all of the viscous friction in the HP-SADM.

4.2 The Gearboxes

The dynamic behaviour of the two gearboxes (one in the SMG and the other between the SMG output shaft and the SADM output shaft) were modelled as a frequency domain model with a gain of 1. The main contribution to the SADM output shaft behaviour is the stiffness of the gearboxes. The model parameters ω_n (natural frequency) and ζ (damping ratio) were derived from actual SADM reaction torque measurements.

5. Modelling the Solar Arrays

Four different sizes of solar arrays are envisaged to be used in conjunction with the HP-SADM. The array manufacturer defines the array dynamic behaviour as a rigid and flexible inertia system coupled with a torsion spring. See Fig 5 below

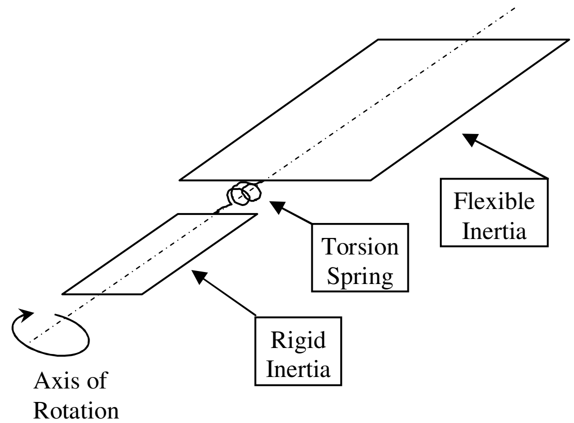

Figure 5, Definition of a Solar Array

In conjunction with the inertia and spring constant parameters, the array manufacturer also publishes a “Q” value. This “Q” value relates to the likely natural damping properties of the array where:

$$\zeta = \frac{C_{CRITICAL}}{Q} \qquad (8)$$

The flexible inertia parameter, the Q value and the spring constant is used to construct a frequency domain model with a gain of 1. Now the model can predict the oscillatory behaviour of the arrays, which in turn will allow the calculation of the torque produced by the oscillating array. This torque is fed back in to the HP-SADM gear train to ensure that no miss-stepping is predicted. The SA manufacturers stipulate a ±10% margin on inertia and ±15% on the spring constant. This leads to a large change in an array's possible natural frequency. These parameter changes are easily realised in the MATLAB™ model.

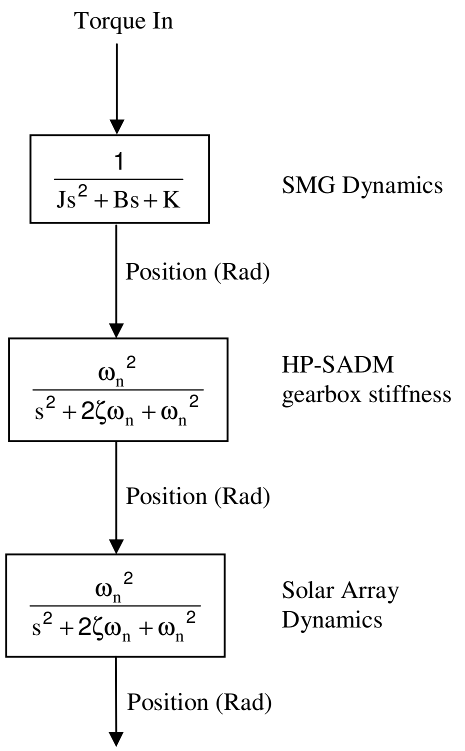

Figure 6. MATLAB™ Model Philosophy

6. CORRELATION OF THE MATLAB MODEL

6.1 Correlation of the SMG

The SMG correlation is achieved by using the BEMF measurements.

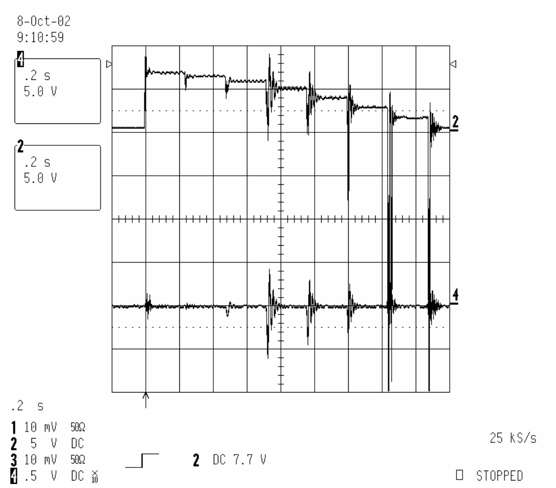

Figure 7, 1RPD BEMF Plot

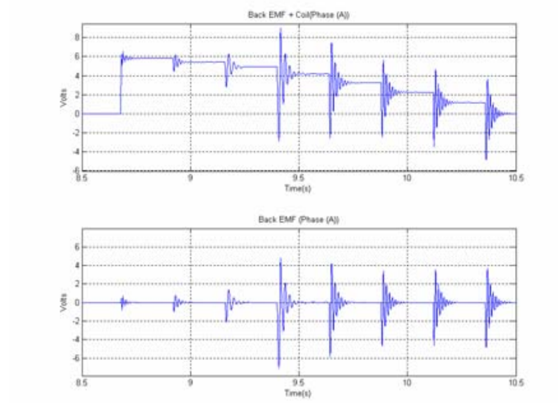

Figure 8, MATLAB™ Model BEMF 1RPD Simulation

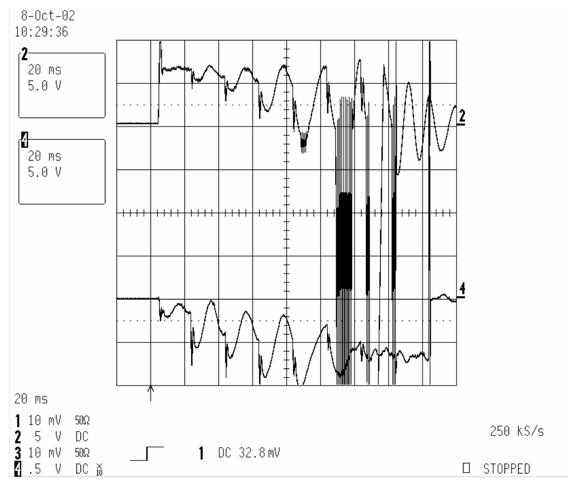

Figure 9, 20RPD BEMF Plot

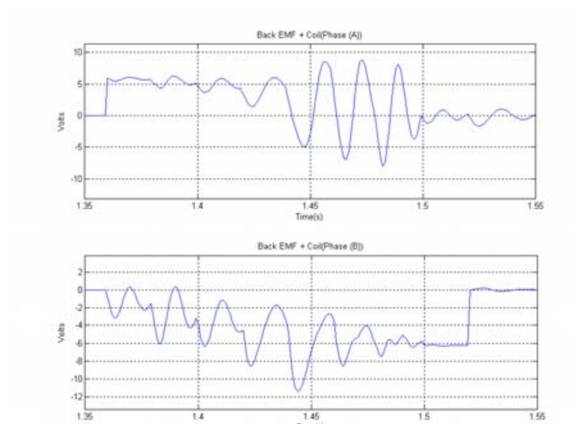

Figure 10, MATLAB™ Model BEMF 20RPD Simulation

Figure 7 is a plot of two BEMF voltages measured on the active and redundant coils at a speed of 1RPD. Figure 8 is a simulation of the BEMF voltages present on the active and redundant motor coils. During correlation of these results, it became apparent that the shape of the graph is sensitive to the difference in the powered on and off natural detent angular position. Figures 9 and 10 show the same plots, but this time at the higher speed of 20RPD. The SADM is only driven at these two speeds. The correlation of the model at these two speeds has led to increased confidence in the models predictions.

6.2 Correlation of the Gearbox Stiffness

The correlation of the SADM gearbox stiffness is achieved by comparing the measured disturbance torque with the simulated disturbance torque. Disturbance torque is measured by mounting the SADM on a Kistler static torque transducer, and then measuring the reaction of the SADM to driving a mass of known inertia.

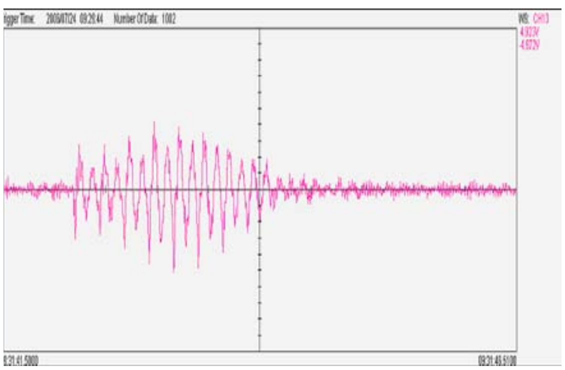

Figure 11, 1RPD Measured Disturbance Torque.

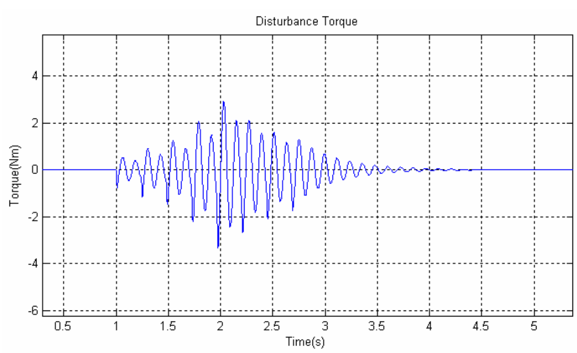

Figure 12, 1RPD Simulated Disturbance Torque

The 1 RPD case shown in Figures 11 and 12 clearly show the 8 mini-steps as downward vertical peaks, the oscillations in-between are due to the SADM gearbox stiffness.

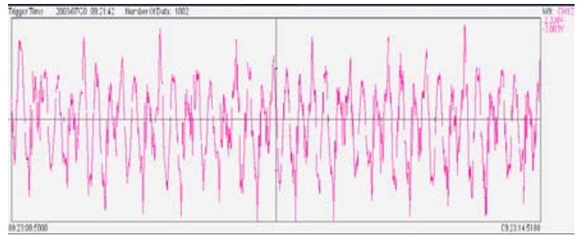

Figure 13, 20 RPD Measured Disturbance Torque

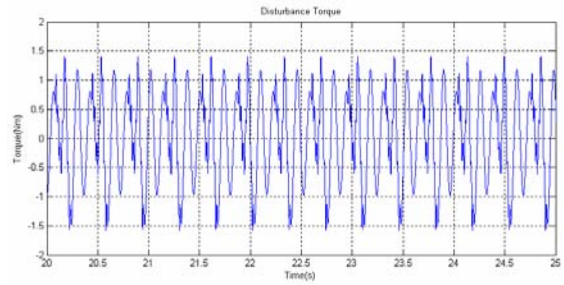

Figure 14, 20 RPD Simulated Disturbance Torque

Figures 13 and 14 show the correlation of the MATLAB™ model to the 20RPD speed disturbance torque plots.

7. MATLAB™ SIMULATION OF THE SOLAR ARRAYS

The MATLAB™ model simulation of the solar arrays indicated that one of the arrays could oscillate significantly when driven by the HP-SADM. This is a very worse case as the array parameters required to cause matching SADM and SA natural frequencies are at the limit of the array manufacture uncertainty margin of ±15% on SA natural frequency. Any slight change to the array frequency will reduce the amplitude markedly as shown in Fig 15.

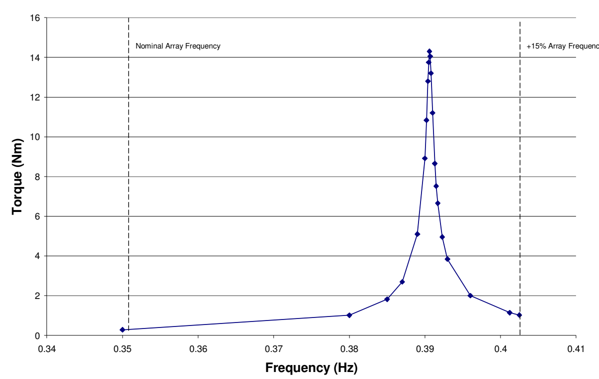

Figure 15, Reduction of SA Torque due to SA Natural Frequency Shift.

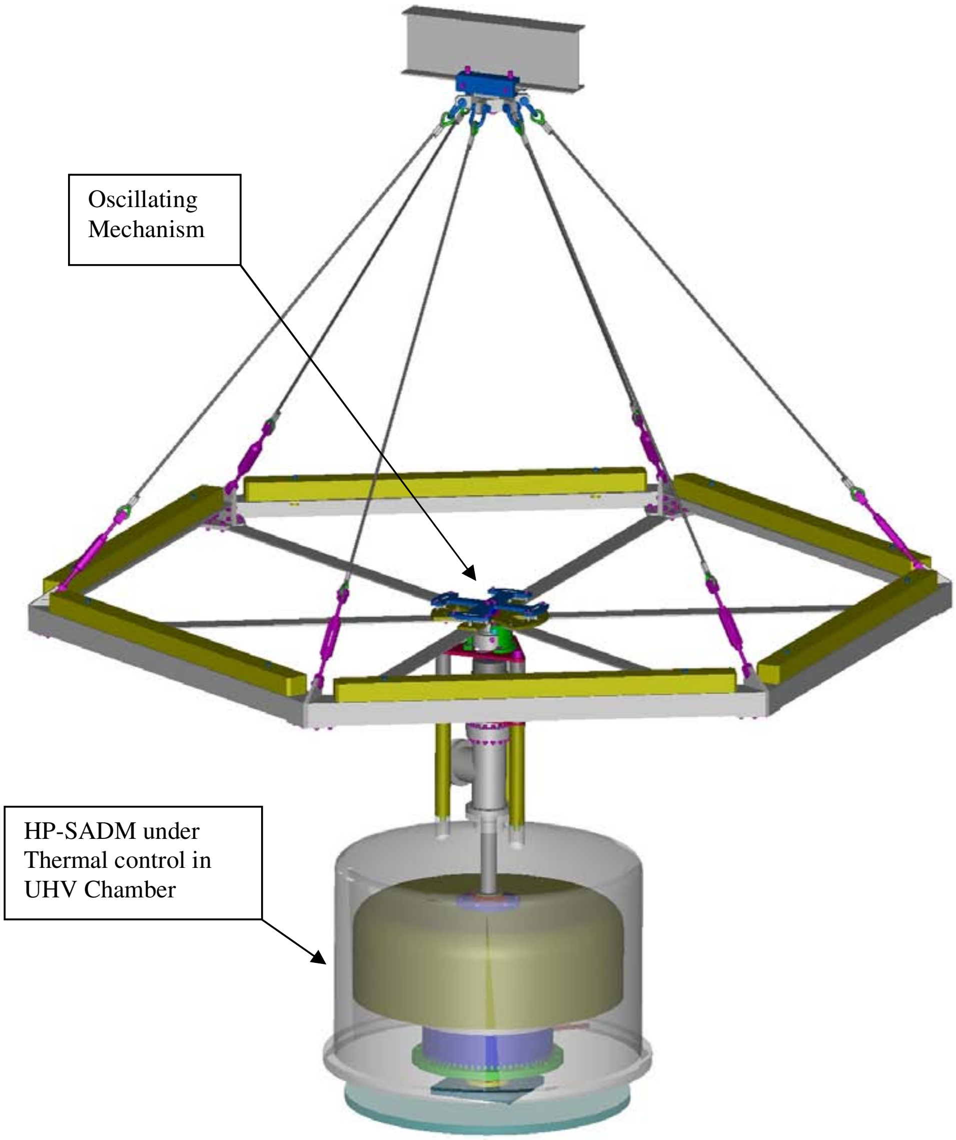

Figure 16, Solar Array Simulator

8. SOLAR ARRAY SIMULATOR

Astrium have designed a solar array simulator in order to ensure that the HP-SADM can drive oscillating solar arrays.
The SAS (Solar Array Simulator) has been designed to mimic as close as possible, the in-orbit oscillatory behaviour of the SA's whilst subjecting the HP-SADM to the environment it will see in space.
Fig 16 is a 3D representation of the SAS (Solar Array Simulator). It consists of a large ring inertia, a spring-loaded mechanism to give the oscillations, and a HP-SADM mounted in a UHV (Ultra High Vacuum) Chamber.

8.1 The Inertia Ring.

The largest SA that will be driven by the SADM has an inertia of 560kgm^2, and a natural frequency of 0.1Hz. In order to achieve the required inertia a framework has been designed. Stainless steel weights are added to this framework in order to increase the mass up to 280kg to achieve the 560kgm^2 inertia. The inertia framework is suspended from an I-Beam through a large thrust bearing to allow it to rotate freely.

8.2 The Oscillating Mechanism

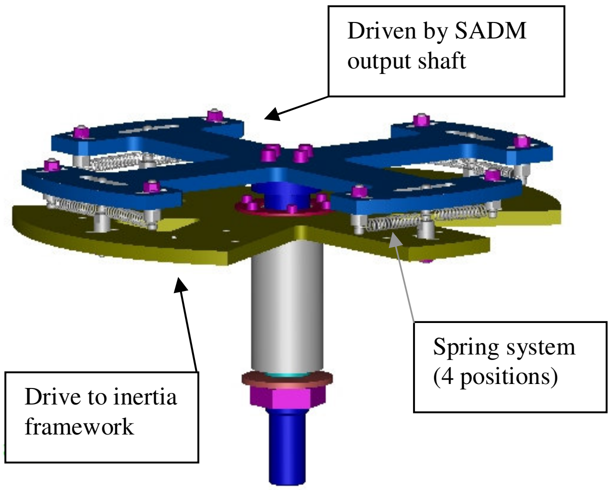

Figure 17, SAS Oscillating Mechanism

The oscillating mechanism transmits the torque from the SADM output shaft to the Inertia framework through a series of springs. The torque generated by the spring system is adjustable in order to fine-tune the SAS and to allow at least two correlation points. As the springs extend and compress in reaction to the SADM output torque they will start to rotate the inertia framework at the required frequency.

8.3 SADM Verification using the Solar Array Simulator

The SAS has been designed to simulate the behaviour of the SA in orbit but it is not possible to recreate the very low decaying of SA oscillations seen in space because of the SAS's bearing frictional losses. This decaying, or 'Q' factor, is due in the context of SA's to losses caused by friction and natural hysteresis seen in a materials force /deflection curve. This inaccuracy will be dealt with by using the MATLAB™ model to simulate the test set-up as well as the in-orbit behaviour. The model can be directly correlated to the test set-up, and then reconfigured to simulate the in orbit behaviour.

The assembly also includes two high-resolution optical encoders to record the SADM drive shaft position and the oscillating inertia position. The SAS has been designed to allow simulation of two or more SA sizes in order to have more than one correlation point.

9. LESSONS LEARNED

The lessons learned so far during this project are all concerned with the design of the SAS. During the simulation of the solar arrays, to understand the torques generated by the SA oscillations it became clear that most of the cases simulated produced torques <2Nm. In order for the SAS to measure these torques accurately, it became necessary to reduce the frictional losses as much as possible. This was achieved by commissioning a specially designed UHV Chamber feed through. This feed through used Ferro fluidic seals to reduce friction.

Other lessons already learned include the need to implement a good stiction / friction model to maximise the correlation accuracy. This area will be further analysed and the model updated once the SAS has moved into the verification phase.

10. CONCLUSIONS

A dynamic mathematical model has been developed and validated against some specific real-life data, namely BEMF results and reaction torque measurements. The SAS is currently being manufactured and then will undergo a test and verification phase in order to fully understand its dynamic behaviour. It is hoped that the SAS development tied in with the subsequent correlation of the MATLAB™ model, will qualify the HP-SADM to drive these large solar arrays.

This paper will be updated for the poster presentation at the ESMATS symposium 2007.